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Prevented mortality and greenhouse gas emissions from historical and projected nuclear power

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Abstract

In the aftermath of the March 2011 accident at Japan's Fukushima Daiichi nuclear power plant, the future contribution of nuclear power to the global energy supply has become somewhat uncertain. Because nuclear power is an abundant, low-carbon source of base-load power, on balance it could make a large contribution to mitigation of global climate change and air pollution. Using historical production data, we calculate that global nuclear power has prevented about 1.84 million air pollution-related deaths and 64 gigatonnes (Gt) CO_2-equivalent greenhouse gas (GHG) emissions that would have resulted from fossil fuel burning. Based on global projection data that take into account the effects of Fukushima, we find that by mid-century, nuclear power could prevent an additional 420,000 to 7.04 million deaths and 80 to 240 $GtCO_2$-eq emissions due to fossil fuels, depending on which fuel it replaces. By contrast, we assess that large-scale expansion of natural gas use would not mitigate the climate problem and would cause far more deaths than expansion of nuclear power.

Introduction

It has become increasingly clear that impacts of unchecked anthropogenic climate change due to GHG emissions from burning of fossil fuels could be catastrophic for both human society and natural ecosystems (in ref *1*, see Figures SPM.2 and 4.4), and that the key time frame for mitigating the climate crisis is the next decade or so[2, 3]. Likewise, during the past decade outdoor air pollution due largely to fossil fuel burning is estimated to cause over 1 million deaths annually worldwide[4]. Nuclear energy (and other carbon-free energy sources) could help to mitigate both of these major problems[5].

The future of global nuclear power will depend largely on choices made by major energy-using countries in the next decade or so[6]. While most of the highly nuclear-dependent countries have affirmed their plans to continue development of nuclear power after the Fukushima accident, several have announced that they will either temporarily suspend plans for new plants or completely phase out existing plants[2]. Serious questions remain about safety, proliferation, and disposal of radioactive waste, which we have discussed in some detail elsewhere[7].

Here, we examine the historical and potential future role of nuclear power with respect to prevention of air pollution-related mortality as well as GHG emissions on multiple spatial scales. Previous studies have quantified global-scale avoided GHG emissions due to nuclear power (e.g., refs *5*, *8*-*10*), however the issue of avoided human deaths remains largely unexplored. We focus on the world as a whole, OECD Europe, and the five countries with the highest annual CO_2 emissions in the last several years. In order, these top five CO_2 emitters are China, United States, India, Russia, and Japan, accounting for 56% of global emissions from 2009-2011[11]. To estimate historically prevented deaths and GHG emissions, we start with data for global annual electricity generation by energy source from 1971-2009 (Figure 1). We then apply mortality and GHG emissions factors, defined respectively as deaths and emissions per unit electric energy generated, for relevant electricity sources (Table 1). For the projection period (2010-2050), we base our estimates on recent (post-Fukushima) nuclear power trajectories given by the UN International Atomic Energy Agency (IAEA)[6].

Methods

Calculation of prevented mortality and GHG impacts

For the historical period (1971-2009), we assume that all nuclear power supply in a given country and year would instead have been delivered by fossil fuels (specifically coal and natural gas), given their worldwide dominance and the very small contribution of non-hydro renewables to world electricity thus far (Figure 1). There are, of course, numerous complications involved in trying to design such a replacement scenario (e.g., evolving technological and socioeconomic conditions), and the retroactive energy mix cannot be known with total accuracy and realism; thus, simplifying yet tenable assumptions are necessary and justified.

To determine the proportional substitution by coal and gas in our baseline historical scenario, we first examine the world nuclear reactor properties provided by IAEA[12]. Based on typical international values for coal and gas capacity factors (CFs)[13], we then assume that each of the 441 reactors listed in Table 14 of ref *12* with CF > 65% is replaced by coal, and each reactor with CF ≤ 65% is replaced by gas.

For each country x we first calculate $P_i(x)$, the power (*not* energy) generated by each reactor i:

$$P_i(x) = CF_i(x) \times C_i(x) \qquad (1)$$

where CF_i, C_i denote the reactor capacity factor and net capacity, respectively, listed in Table 14 of ref *12*. We then calculate $f_i(x)$, the CF-weighted proportion of generated power by each reactor:

$$f_i(x) = P_i(x) / \sum_i P_i(x) \qquad (2)$$

Next, we calculate $F_j(x)$, the total proportion of generated nuclear power replaced by power from fossil fuel j:

$$F_j(x) = \sum_i f_i^{(j)}(x) \qquad (3)$$

where $f_i^{(j)}(x)$ simply denotes grouping of all the f_i values by replacement fuel j. For reference, on the global scale this yields about 95% replacement by coal and 5% by gas in our baseline historical scenario, which we suggest is plausible for the reasons given in the Discussion section. Lastly, we calculate I(x,t), the annual net prevented impacts (mortality or GHG emissions) from nuclear power in country x and year t as follows:

$$I(x,t) = \sum_j[IF_j \times F_j(x) \times n(x,t)] - IF_n \times n(x,t) \qquad (4)$$

where IF_j = impact factor for fossil fuel j (from Table 1); n(x,t) = nuclear power generation (in energy units); and IF_n = impact factor for nuclear power (from Table 1). Note that the first term in eq 4 reflects gross avoided impacts, while the second reflects direct impacts of nuclear power.

For the projection period (2010-2050), using eq 4 we calculate human deaths and GHG emissions that could result if all projected nuclear power production is canceled and again replaced only by fossil fuels. Of course, some or most of this hypothetically canceled nuclear power could be replaced by power from renewables, which have generally similar impact factors as nuclear (e.g., see Figure 2 of ref *7*). Thus, our results for the projection period should ultimately be viewed as upper limits on potentially prevented impacts from future nuclear power.

We project annual nuclear power production in the regions containing the top five CO_2-emitting countries and Western Europe based on the regional decadal projections in Table 4 of IAEA[6], which we linearly interpolate to an annual scale. To set $F_j(x)$ in eq 4, we consider two simplified cases for both the global and regional scales. In the first ("All Coal"), $F_j(x)$ is fixed at 100% coal, and in the second ("All Gas") it is fixed at 100% gas. This approach yields the full range of potentially prevented impacts from future nuclear power. It is taken here because of the lack of country-specific projections in ref *6* as well as the large uncertainty in determining which fossil fuel(s) could replace *future* nuclear power, given recent trends in electricity production (Figure 1, Figure S3, and ref *14*).

Methodological limitations

The projections for nuclear power by IAEA[6] assume essentially no climate change mitigation measures in the low-end case and aggressive mitigation measures in the high-end case. It is unclear which path the world will follow – however, these IAEA projections *do* take into account the effects of the Fukushima accident. It seems that except possibly for Japan, the top five CO_2-emitting countries are not planning a phase-down of pre-Fukushima plans for future nuclear power. For instance China, India, and Russia have affirmed plans to increase their current nuclear capacity by >3-fold, >12-fold, and 2-fold, respectively (see Table 12.2 of ref *2*). In Japan the future of nuclear power now seems unclear – as of ~1 year following the Fukushima accident, nuclear power generation in Japan decreased by 63%, while fossil fuel power generation increased by 26% (ref *15*), thereby almost certainly increasing Japan's CO_2 emissions.

Although our analysis reflects mortality from all stages of the fuel cycle for each energy source, it excludes serious illnesses, including respiratory and cerebrovascular hospitalizations, chronic bronchitis, congestive heart failure, non-fatal cancers, and hereditary effects. For fossil fuels, such illnesses are estimated to be approximately 10 times higher than the mortality factors in Table 1, while for nuclear power they are ~3 times higher[16]. Another important limitation is that the mortality factors exclude the impacts of anthropogenic climate change and development-related differences, as explained in the Discussion section. Aspects of nuclear power that cannot meaningfully be quantified due to very large uncertainties (e.g. potential mortality from proliferation of weapons-grade material) are also not included in our analysis.

Proportions of fossil fuels in our projection cases are assumed to be fixed (for the purpose of determining upper and lower bounds), but will almost certainly vary across years and decades, as in the historical period (Figure 1). The dominance of coal in the global average electricity mix seems likely for the near future though (e.g., Figure 5.2 of ref *2*). However, even if there is large-scale worldwide electric fuel switching from coal to gas, our assessment is that the ultimate GHG savings from such a transition are unlikely to be sufficient to minimize the risk of dangerous anthropogenic climate change (unless the resulting emissions are captured and stored), as discussed in the next section.

Results and Discussion

Mortality

We calculate a mean value of 1.84 million human deaths prevented by world nuclear power production from 1971-2009 (see Figure 2a for full range), with an average of 76,000 prevented deaths/yr from 2000-2009 (range 19,000–300,000). Estimates for the top five CO_2 emitters, along with full estimate ranges for all regions in our baseline historical scenario, are also shown in Figure 2a. For perspective, results for upper and lower bound scenarios are shown in Figure S1. In Germany, which has announced plans to shut down all reactors by 2022 (ref *2*), we calculate that nuclear power has prevented an average of over 117,000 deaths from 1971-2009 (range 29,000–470,000). The large ranges stem directly from the ranges given in Table 1 for the mortality factors.

Our estimated human deaths *caused* by nuclear power from 1971-2009 are far lower than the avoided deaths. Globally, we calculate 4900 such deaths, or about 370 times lower than our result for avoided deaths. Regionally, we calculate approximately 1,800 deaths in OECD Europe; 1,500 in USA; 540 in Japan; 460 in Russia (includes all 15 Former Soviet Union countries); 40 in China; and 20 in India. About 25% of these deaths are due to occupational accidents and about 70% are due to air pollution-related effects (presumably fatal cancers from radiation fallout; see Table 2 of ref *16*).

However, empirical evidence indicates that the April 1986 Chernobyl accident was the world's only source of fatalities from nuclear power plant radiation fallout. According to the latest assessment by the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR)[17], 43 deaths are conclusively attributable to radiation from Chernobyl as of 2006 (28 were plant staff/first responders and 15 were from the 6,000 diagnosed cases of thyroid cancer). UNSCEAR[17] also states that reports of an increase in leukemia among recovery workers who received higher doses are inconclusive, although cataract development was clinically significant in that group; otherwise, for these workers as well as the general population, "there has been no persuasive evidence of any other health effect" attributable to radiation exposure[17].

Furthermore, no deaths have been conclusively attributed (in a scientifically valid manner) to radiation from the other two major accidents, i.e. Three Mile Island in March 1979, for which a 20-year comprehensive scientific health assessment was done[18]; and the March 2011 Fukushima Daiichi accident. While it is too soon to meaningfully assess the health impacts of the latter accident, one early analysis[19] indicates that annual radiation doses in nearby areas were much lower than the generally accepted 100 mSv threshold[17] for fatal disease development. In any case, our calculated value for global deaths caused by historical nuclear power (~4,900) could be a major overestimate relative to the empirical value (by 2 orders of magnitude). The absence of evidence of large mortality from past nuclear accidents is consistent with recent findings[20, 21] that the "linear no-threshold" model used to derive the nuclear mortality factor in Table 1 (see ref *22*) might not be valid for the relatively low radiation doses that the public was exposed to from nuclear power plant accidents.

For the projection period (2010-2050), we find that in the All Coal case (see Methods), an average of 4.39 million and 7.04 million deaths are prevented globally by nuclear power production for the low-end and high-end projections of IAEA[6], respectively, while in the All Gas case, an average of 420,000 and 680,000 deaths are prevented globally (see Figure 2b,c for full ranges). Regional results are also shown in Figure 2b,c. The Far East and North America have particularly high values, given that they are projected to be the biggest nuclear power producers (Figure S2). As in the historical period, calculated deaths caused by nuclear power in our projection cases are far lower (2 orders of magnitude) than the avoided deaths, even taking the nuclear mortality factor at face value (despite the discrepancy with empirical data discussed above for the historical period).

The substantially lower deaths in the projected All Gas case follow simply from the fact that gas is estimated to have a mortality factor an order of magnitude lower than coal (Table 1). However, this does not necessarily provide a valid argument for such large-scale "fuel switching" for mitigation of either climate change or air pollution, for several reasons. First, it is important to bear in mind that our results for prevented mortality are likely conservative, because the mortality factors in Table 1 do not incorporate impacts of ongoing or future anthropogenic climate change[16]. These impacts are likely to become devastating for both human health and ecosystems if recent global GHG emission trends continue[1, 3]. Also, potential global natural gas resources are enormous – e.g., published estimates for technically recoverable unconventional gas resources suggest a carbon content ranging from >700 $GtCO_2$ (based on refs *23*, *24*) to >17,000 $GtCO_2$ (based on refs *24*, *25*). While we acknowledge that natural gas might play an important role as a "transition" fuel to a clean-energy era due to its lower mortality (and emission) factor relative to coal, we stress that long-term, widespread use of natural gas (without accompanying carbon capture and storage) could lead to unabated GHG emissions for many decades, given the typically multi-decadal lifetime of energy infrastructure -- thereby greatly complicating climate change mitigation efforts.

GHG emissions

We calculate that world nuclear power generation prevented an average of 64 $GtCO_2$-eq (or 17 GtC-eq) of cumulative emissions from 1971-2009 (Figure 3a; see full range therein), with an average of 2.6 $GtCO_2$-eq/yr prevented annual emissions from 2000-2009 (range 2.4–2.8 $GtCO_2$/yr). Regional results are also shown in Figure 3a. Our global results are 7-14% lower than previous estimates[8, 9] that, among other differences, assumed all historical nuclear power would have been replaced only by coal; and 34% higher than in another study[10] in which the methodology is not explained clearly enough to infer the basis for the differences. Given that cumulative and annual global fossil fuel CO_2 emissions during the above periods were 840 $GtCO_2$ and 27 $GtCO_2$/yr respectively[11], our mean estimate for cumulative prevented emissions may not appear substantial – however it is instructive to look at other quantitative comparisons.

For instance, 64 $GtCO_2$-eq amounts to the cumulative CO_2 emissions from coal burning over approximately the past 35 yr in USA, 17 yr in China, or 7 yr in the top five CO_2 emitters[11]. Also, since a 500-MW coal-fired power plant typically emits 3 $MtCO_2$/yr[26], 64 $GtCO_2$-eq is equivalent to the cumulative lifetime emissions from almost 430 such plants, assuming an average plant lifetime of 50 yr. It is therefore evident that without global nuclear power generation in recent decades, near-term mitigation of anthropogenic climate change would pose a much greater challenge.

For the projection period (2010-2050), in the All Coal case an average of 150 and 240 $GtCO_2$-eq cumulative global emissions are prevented by nuclear power for the low-end and high-end projections of IAEA[6], respectively, while in the All Gas case, an average of 80 and 130 $GtCO_2$-eq emissions are prevented (see Figure 3b,c for full ranges). Regional results are also shown in Figure 3b,c. These results also differ substantially from previous studies[9, 10], largely due to differences in nuclear power projections (see SI).

To put our calculated overall mean estimate (80-240 $GtCO_2$-eq) of potentially prevented future emissions in perspective, note that to achieve a 350 ppm CO_2 target near the end of this century, cumulative "allowable" fossil CO_2 emissions from 2012 to 2050 are at most ~500 $GtCO_2$ (ref *3*). Thus, projected nuclear power could reduce the climate change mitigation burden by 16-48% over the next few decades (derived by dividing 80 and 240 by 500).

Uncertainties

Our results contain various uncertainties, primarily stemming from our impact factors (Table 1) and our assumed replacement scenarios for nuclear power. In reality the impact factors are not likely to remain static, as we (implicitly) assumed – for instance, emission factors depend heavily on the particular mix of energy sources. Because the factors in Table 1 neglect ongoing or projected climate impacts as well as the significant disparity in pollution between developed and developing countries[16], our results for both avoided GHG emissions and avoided mortality could be substantial underestimates. For example, in China, where coal burning accounts for over 75% of electricity generation in recent decades (ref *14*; Figure S3), some coal-fired power plants that meet domestic environmental standards have a mortality factor almost 3 times higher than the mean global value (Table 1). These differences related to development status will become increasingly important as fossil fuel use and GHG emissions of developing countries continue to outpace those of developed countries[11].

On the other hand, if coal would not have been as dominant a replacement for nuclear as assumed in our baseline historical scenario, then our avoided historical impacts could be overestimates, since coal causes much larger impacts than gas (Table 1). However, there are several reasons this is unlikely. Key characteristics of coal plants (e.g., plant capacity, capacity factor, and total production costs) are historically much more similar to nuclear plants than are those of natural gas plants[13]. Also, the vast majority of existing nuclear plants were built before 1990, but advanced gas plants that would be suitable replacements for base-load nuclear plants (i.e., combined-cycle gas turbines) have only become available since the early 1990s[13]. Furthermore, coal resources are highly abundant and widespread[24,25] and coal fuel and total production costs have long been relatively low, unlike historically available gas resources and production costs[13]. Thus, it is not surprising that coal has been by far the dominant source of global electricity thus far (Figure 1). We therefore assess that our baseline historical replacement scenario is plausible and that it is not as significant an uncertainty source as the impact factors – i.e., our avoided historical impacts are more likely underestimates, as discussed in the above paragraph.

Implications

More broadly, our results underscore the importance of avoiding a false and counterproductive dichotomy between reducing air pollution and stabilizing the climate, as elaborated by others[27-29]. If near-term air pollution abatement trumps the goal of long-term climate protection, governments might decide to carry out future electric fuel switching in much more climate-impacting ways than we have examined here. For instance, they might start large-scale production and use of gas derived from coal ("syngas"), as coal is by far the most abundant of the three conventional fossil fuels[24, 25]. While this could reduce the very high pollution-related deaths from coal power (Figure 2), the GHG emissions factor for syngas is substantially higher (between ~5-90%) than for coal[30], thereby entailing even higher electricity sector GHG emissions in the long term.

In conclusion, it is clear that nuclear power has provided a large contribution to the reduction of global mortality and GHG emissions due to fossil fuel use. If the role of nuclear power significantly declines in the next few decades, the International Energy Agency asserts that achieving a target atmospheric GHG level of 450 ppm CO_2-eq would require "heroic achievements in the deployment of emerging low-carbon technologies, which have yet to be proven. Countries that rely heavily on nuclear power would find it particularly challenging and significantly more costly to meet their targeted levels of emissions."[2] Our analysis herein and a prior one[7] strongly support this conclusion. Indeed, based on combined evidence from paleoclimate data, observed ongoing climate impacts, and the measured planetary energy imbalance, it appears increasingly clear that the commonly discussed targets of 450 ppm and 2°C global temperature rise (above preindustrial levels) are insufficient to avoid devastating climate impacts – we have suggested elsewhere that more appropriate targets are <350 ppm and 1°C (refs *3*, *31-33*). Achieving these targets emphasizes the importance of retaining and expanding nuclear power, as well as carbon-free renewables, in the near-term global energy supply.

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Supporting Information Available
Supplemental discussion and three supplemental figures accompany this article. This information is available free of charge via the Internet at http://pubs.acs.org/.

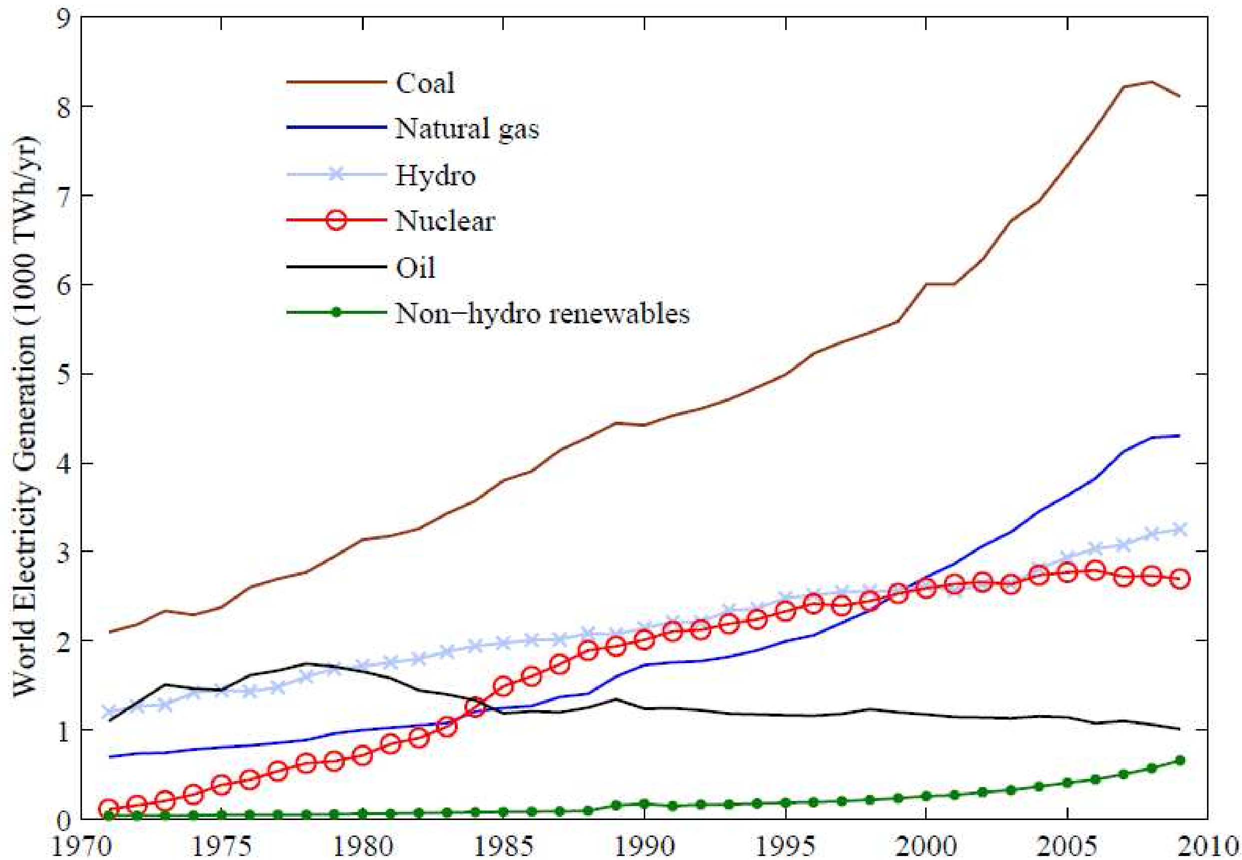

Figure 1. World electricity generation by power source for 1971-2009 (data from ref *14*). In the last decade (2000-2009), nuclear power provided an average 15% of world generation; coal, gas, and oil provided 40%, 20%, and 6%, respectively; and renewables provided 16% (hydropower) and 2% (non-hydro).

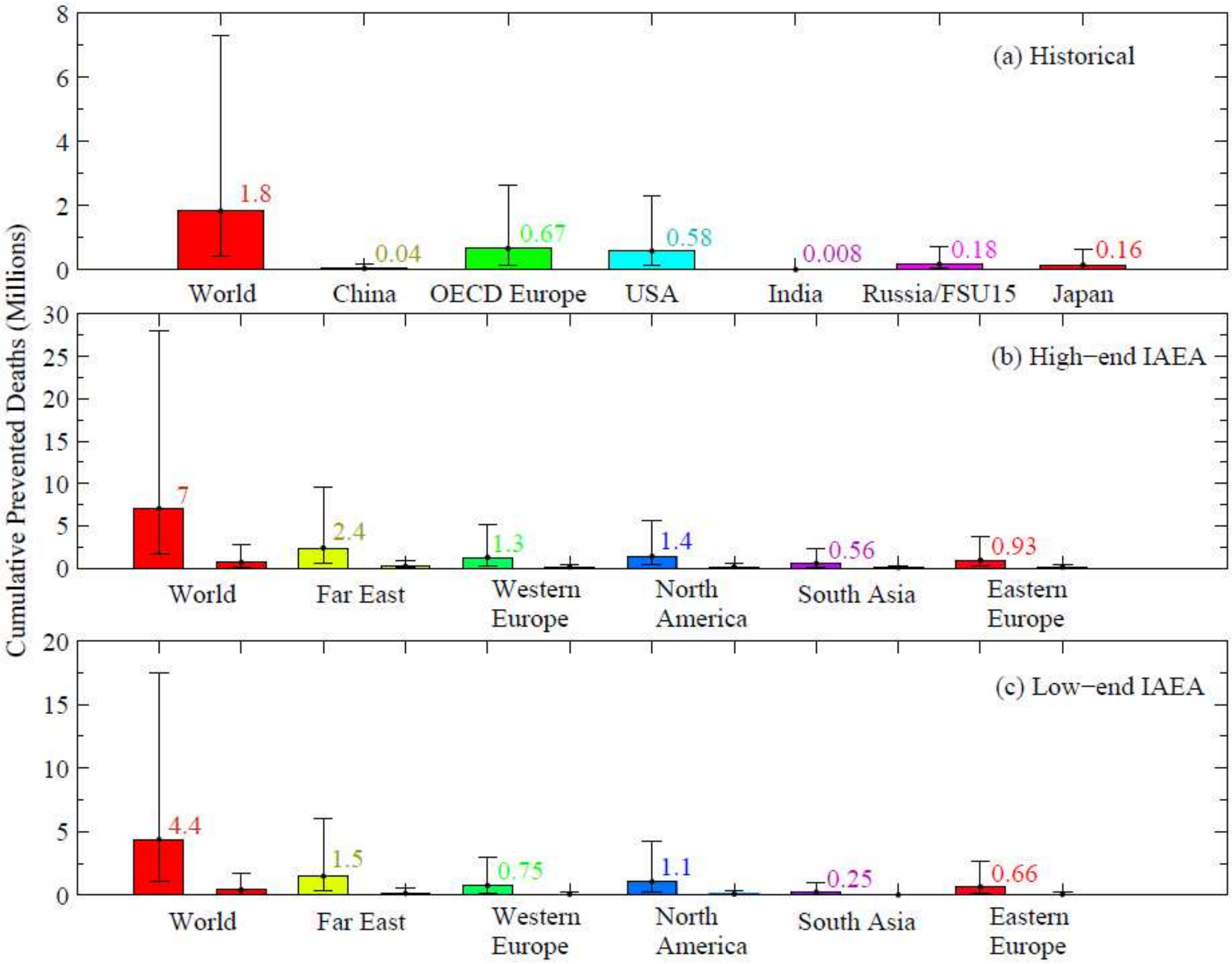

Figure 2. Cumulative net deaths prevented assuming nuclear power replaces fossil fuels. Results for (a) the historical period in our study (1971-2009), showing mean values (labeled) and ranges for the baseline historical scenario. Results for (b) the high-end and (c) low-end projections of nuclear power production by the UN International Atomic Energy Agency[6] for the period 2010-2050. Error bars reflect the ranges for the fossil fuel mortality factors listed in Table 1. The larger columns in panels b and c reflect the All Coal case and are labeled with their mean values, while the smaller columns reflect the All Gas case; values for the latter are not shown because they are all simply a factor of ~10 lower (reflecting the order-of-magnitude difference between the mortality factors for coal and gas shown in Table 1). Countries/regions are arranged in descending order of CO_2 emissions in recent years. FSU15=15 countries of the Former Soviet Union and OECD=Organization for Economic Cooperation and Development.

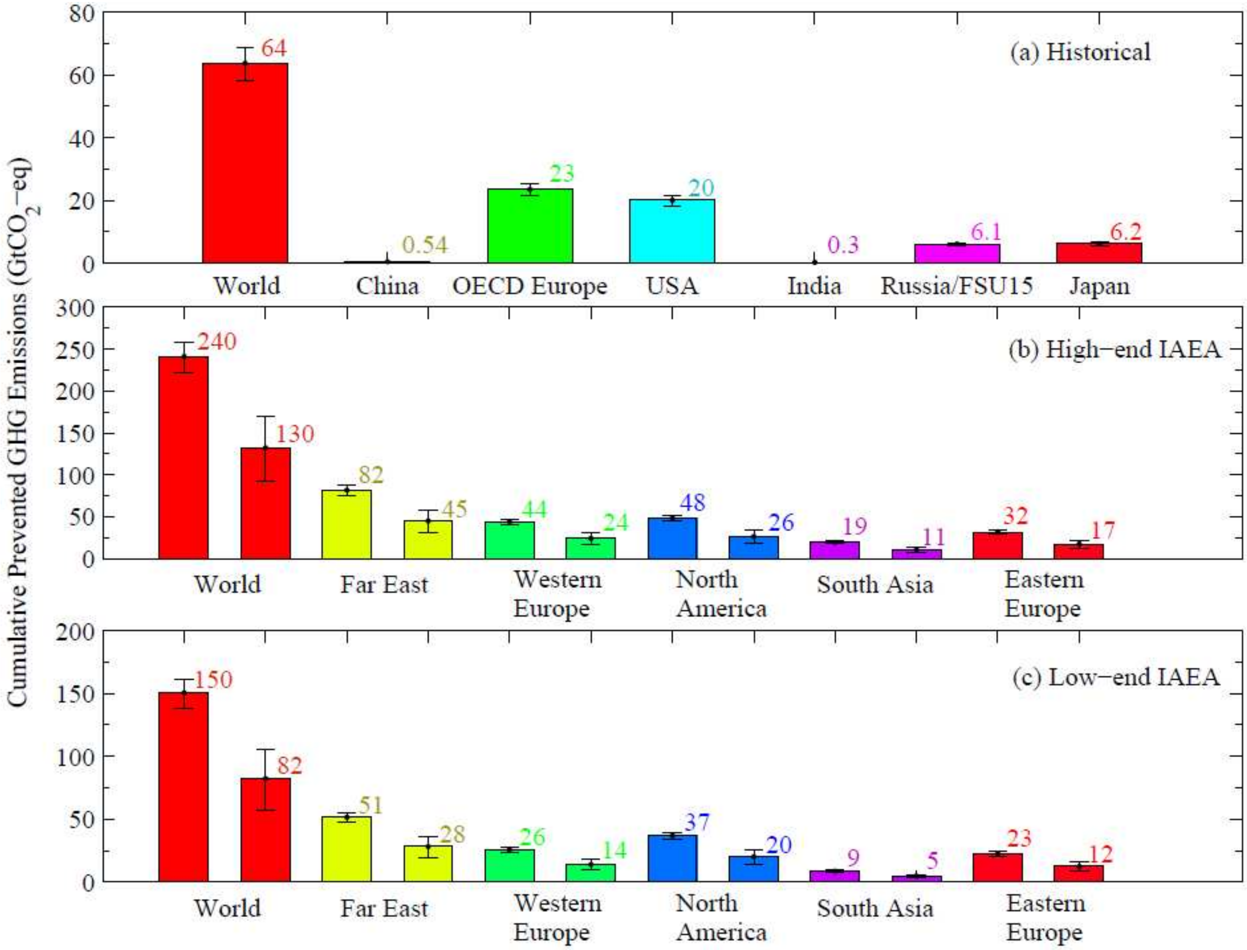

Figure 3. Cumulative net GHG emissions prevented assuming nuclear power replaces fossil fuels. Same panel arrangement as Figure 2, except mean values for all cases are labeled. Error bars reflect the ranges for the fossil fuel emission factors listed in Table 1.

Table 1. Mortality and GHG emission factors used in this study. Mortality factors are based on analysis for Europe (except as indicated) and represent the sum of accidental deaths and air pollution-related effects in Table 2 of ref *16*. They reflect impacts from all stages of the fuel cycle, including fuel extraction, transport, transformation, waste disposal, and electricity transport. Their ranges are 95% confidence intervals and represent deviation from the mean by a factor of ~4. Mortality factor for coal is the mean of the factors for lignite and coal in ref *16*. Mean values for emission factors are the midpoints of the ranges given in the sources. Water pollution is also a significant impact but is not factored into these values. Additional uncertainties and limitations inherent in these factors are discussed in the text.

Electricity source	Mean value *(Range)*	Unit	Source
Coal	28.67 *(7.15-114)*	deaths/TWh	ref *16*
	77 (19.25-308)	deaths/TWh	ref *16* (China)*
	1045 *(909-1182)*	tCO_2-eq/GWh	ref *30*
Natural gas	2.821 *(0.7-11.2)*	deaths/TWh	ref *16*
	602 *(386-818)*	tCO_2-eq/GWh	ref *30*
Nuclear	0.074 *(range not given)*	deaths/TWh	ref *16*
	65 *(10-130)***	tCO_2-eq/GWh	ref *34*

TWh = terawatt-hr, GWh = gigawatt-hr; tCO_2-eq = tonnes CO_2-equivalent emissions.
*Range not given in source for China, but for consistency with other factors, assumed to be 4 times lower and higher than mean
**Some authors contend the upper limit is significantly higher, but their conclusions are based on dubious assumptions[35]

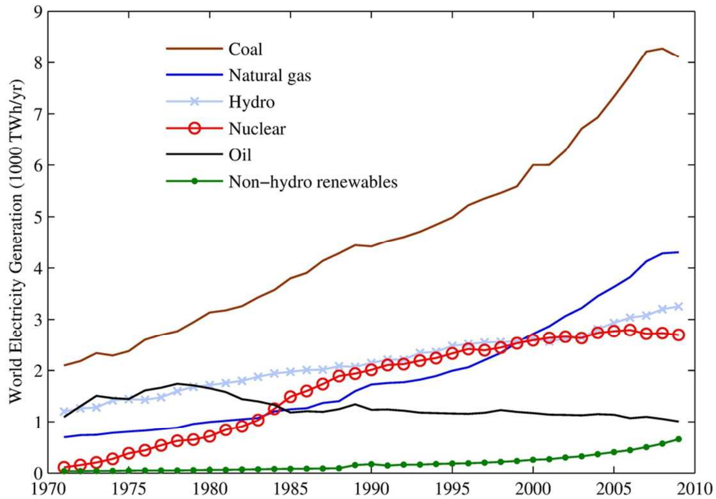

Figure 1. World electricity generation by power source for 1971-2009 (data from ref 14). In the last decade (2000-2009), nuclear power provided an average 15% of world generation; coal, gas, and oil provided 40%, 20%, and 6%, respectively; and renewables provided 16% (hydropower) and 2% (non-hydro).
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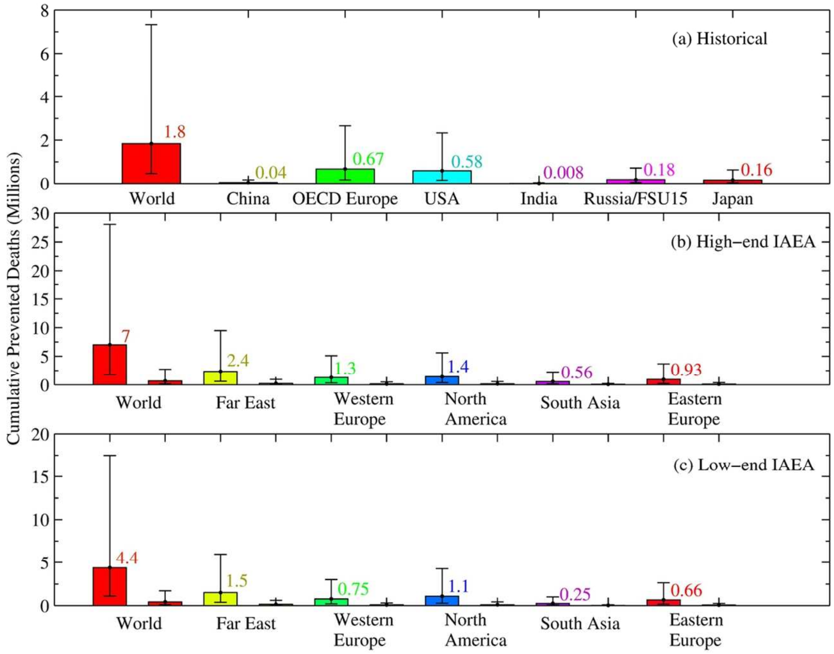

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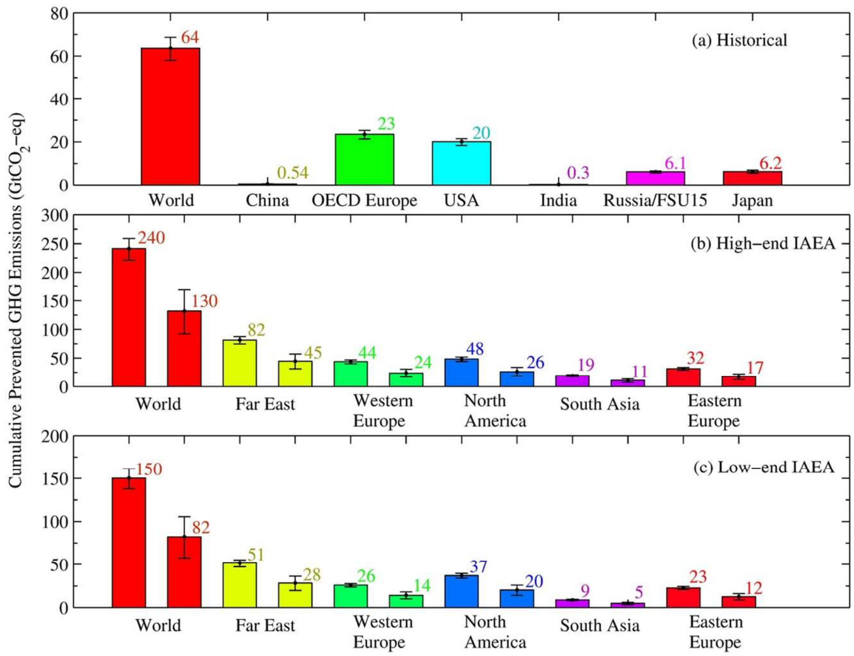

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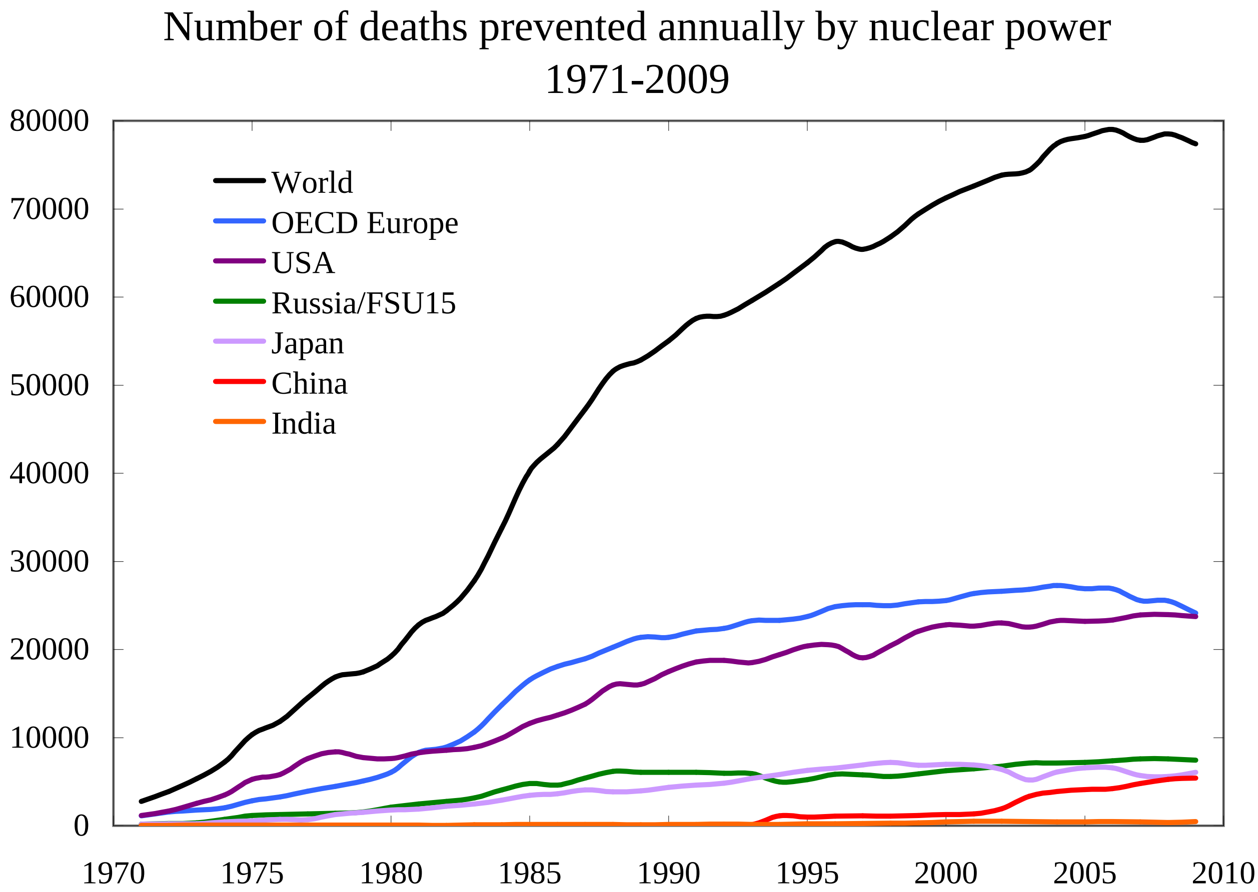
Number of deaths prevented annually by nuclear power
1971-2009
80000
70000
60000
50000
40000
30000
20000
10000
0
1970
1975
1980
1985
1990
1995
2000
2005
2010
World
OECD Europe
USA
Russia/FSU15
Japan
China
India